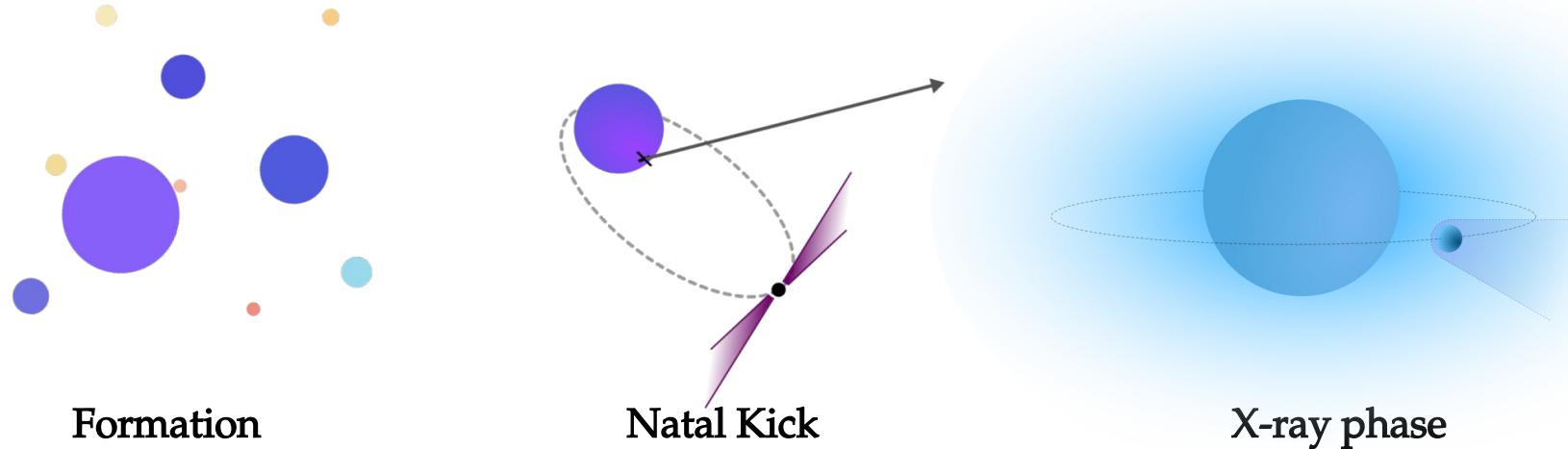


# Formation of high-mass X-ray binaries: natal kick and migration through the Galaxy

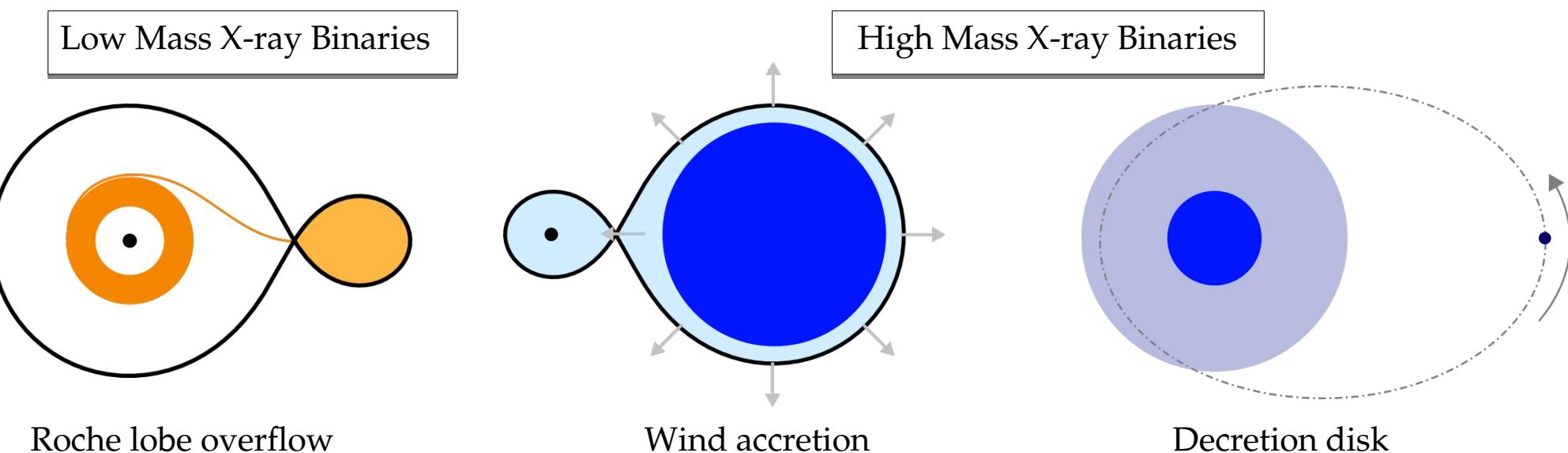


Francis Fortin – Postdoc LabEx UnivEarthS – APC

# X-ray binaries cheat sheet

- Discovered in the 1960'
- Hard X-ray emission powered by accretion
- Transient or persistent
- Disks, jets, stellar winds...

Companion star: low mass ( $< 1 M_{\odot}$ ) or high mass ( $> 8 M_{\odot}$ )



Roche lobe overflow

Wind accretion

Decretion disk

# Evolution of High-Mass X-ray Binaries (HMXBs)

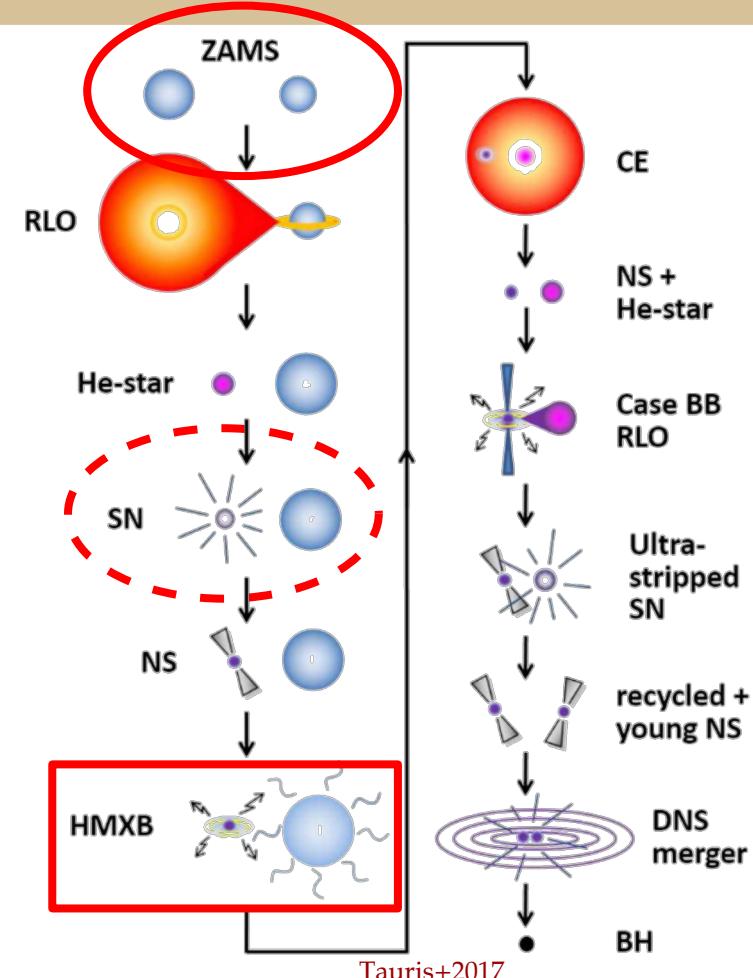
- X-ray systems : just a phase in the life of a binary

Preceded by :

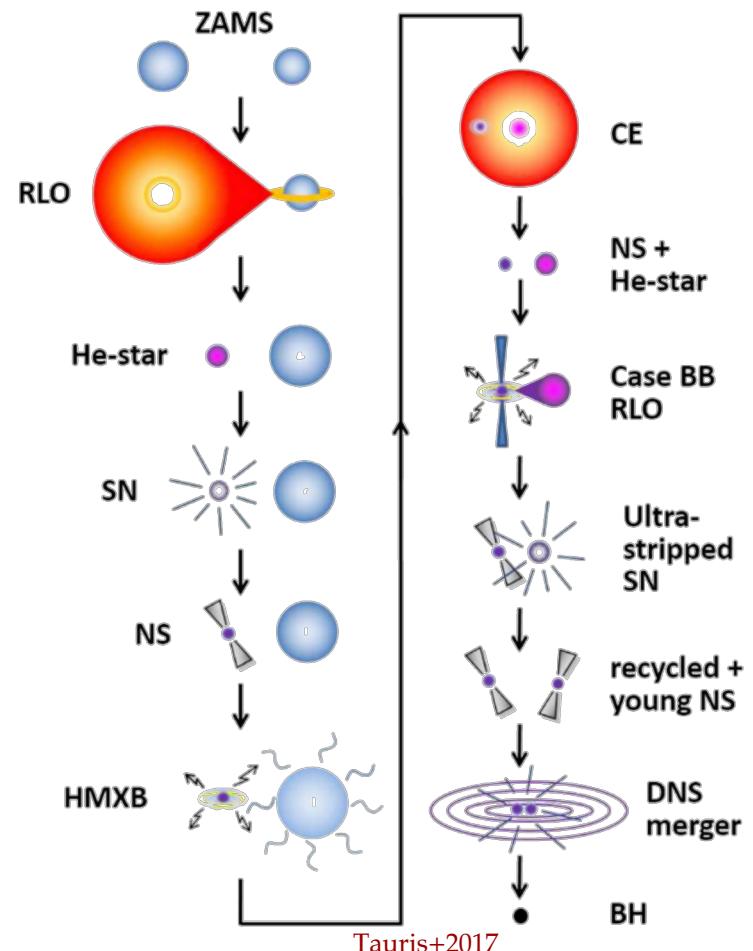
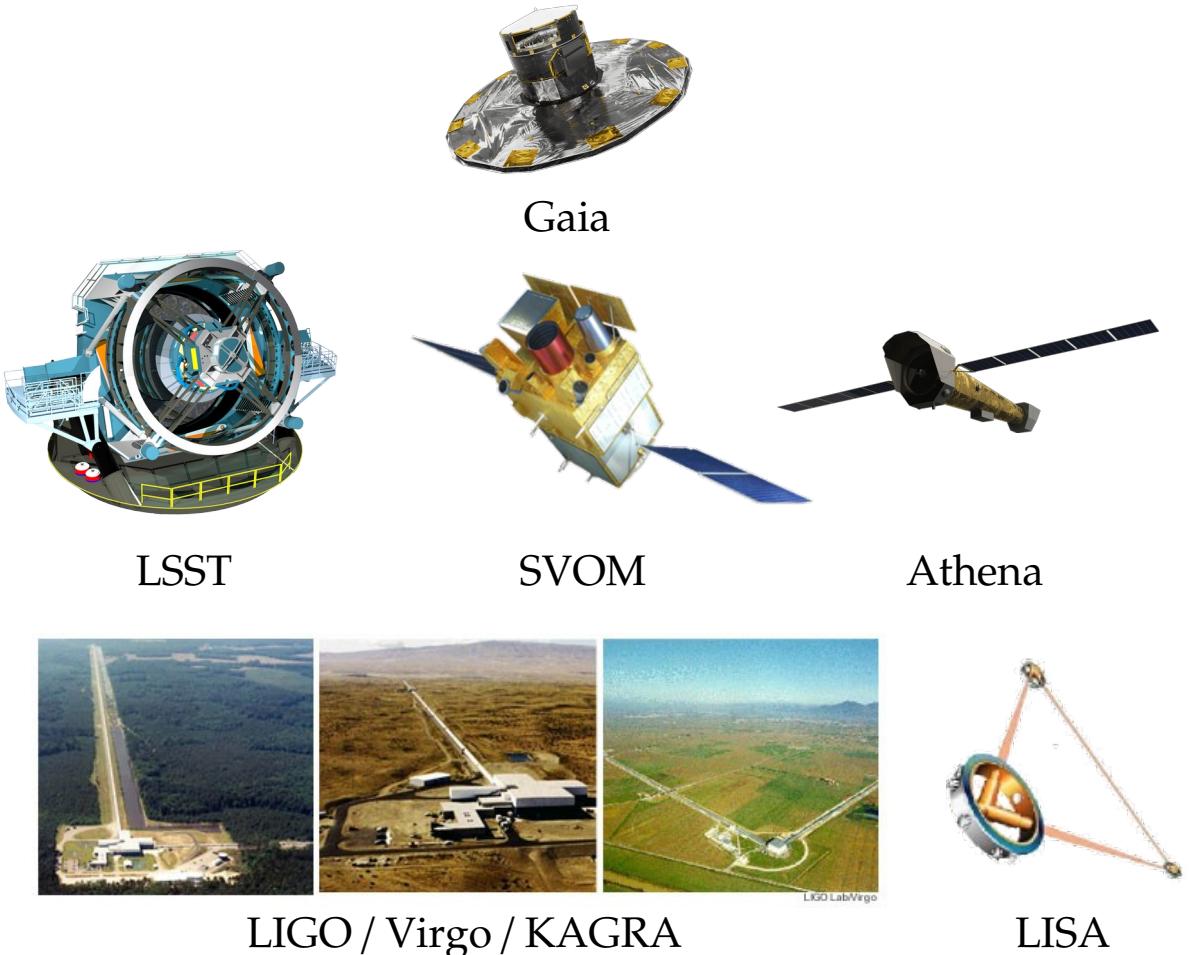
- supernova event
- initial mass transfer

Followed by :

- common envelope
- mass transfer
- another supernova
- final compact merger



# Observational prospects

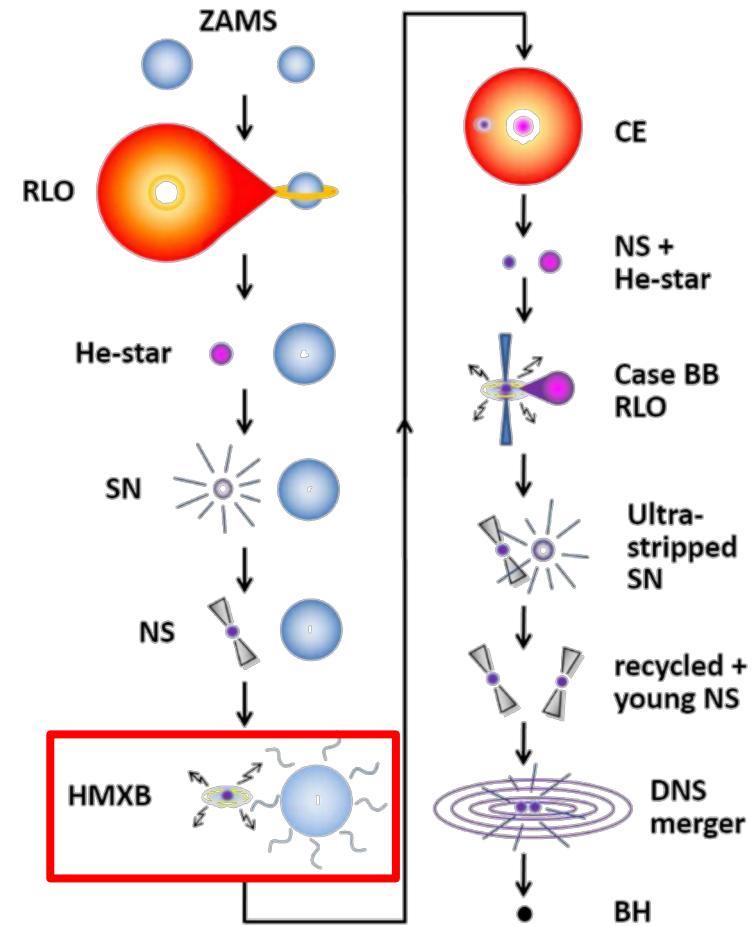


# Observing the history of binary star systems

I – A catalogue of HMXBs in the Galaxy

II – Impact of the natal kick in binaries

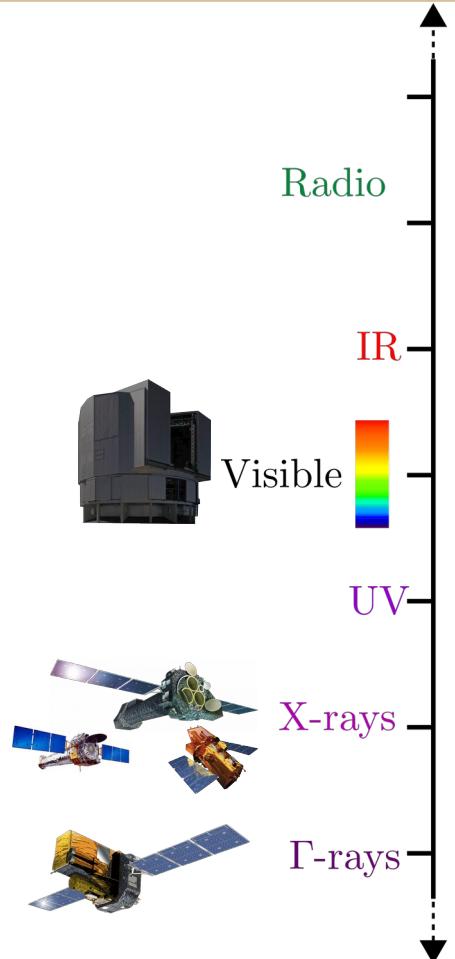
III – Finding the birthplace of stellar systems



# X-ray binaries: observational challenges

- 1) discovery in hard X-rays
- 2) better localization in soft X-rays
- 3) precise counterpart in optical/nIR
  - spectral type of the companion star ?
  - (super)orbital period ?
  - spin period ?
  - radial velocity follow-up ?
  - variability ?

→ Many years & observations are necessary to constrain XRBs

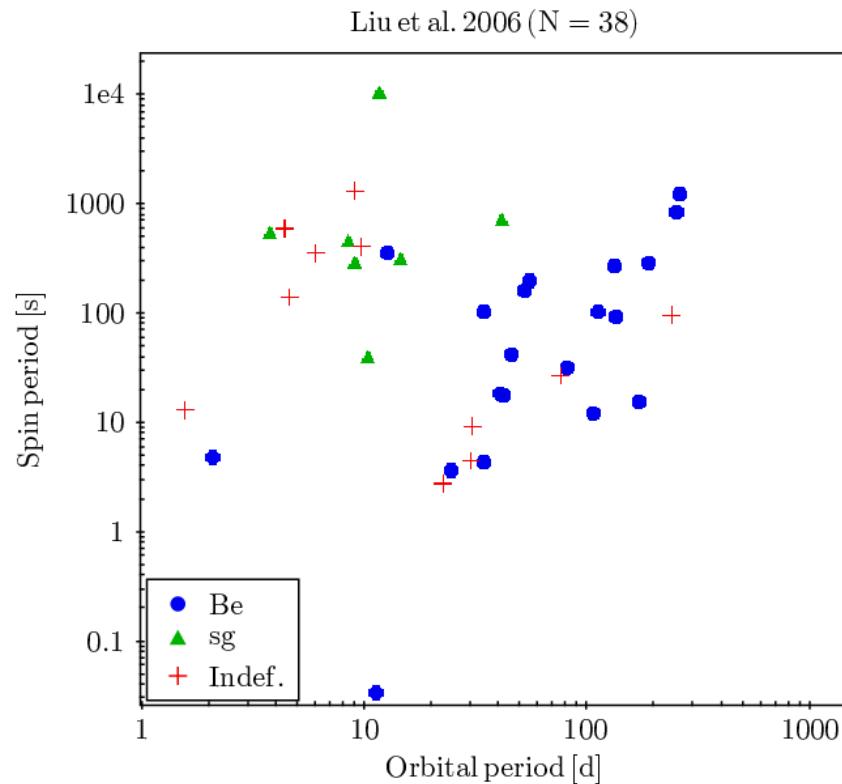
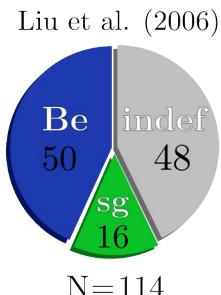


# The new catalogue of HMXBs in the Galaxy

Last catalogue of HMXBs : Liu et al. 2006 [114]

→ many new observations since then

→ INTEGRAL was just beginning !



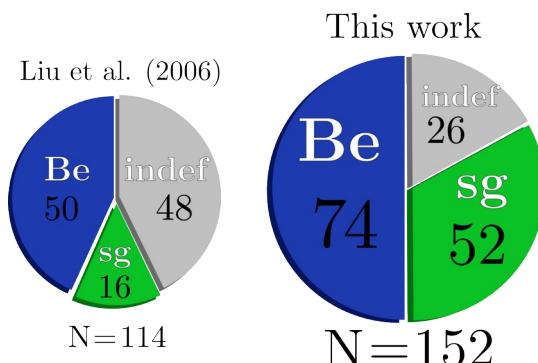
# The new catalogue of HMXBs in the Galaxy

Last catalogue of HMXBs : Liu et al. 2006 [114]

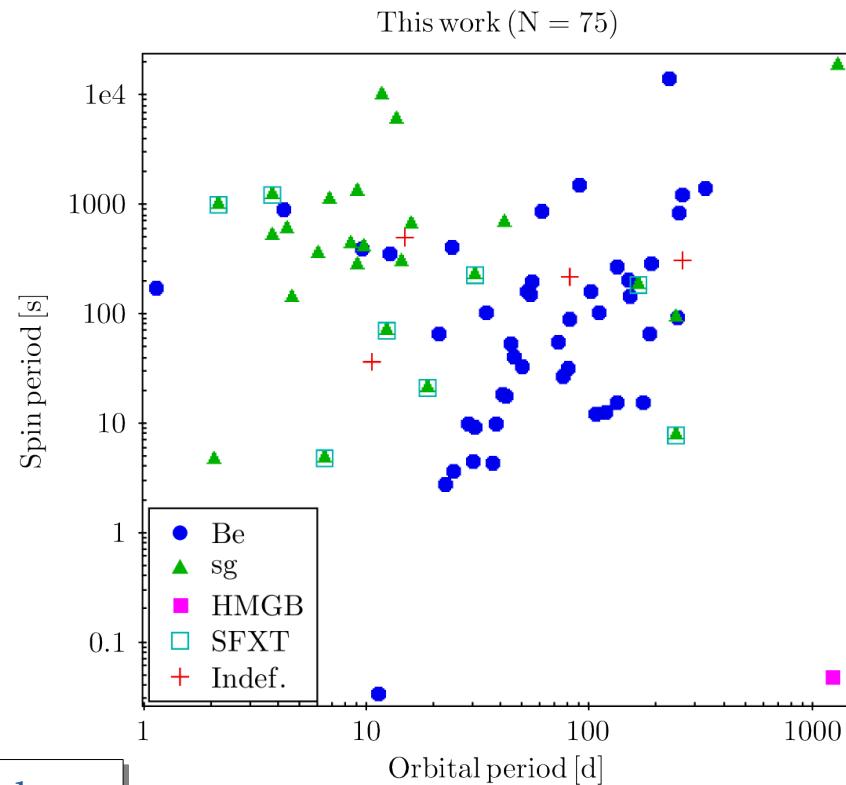
- many new observations since then
- INTEGRAL was just beginning !

New catalogue of HMXBs : Fortin et al. 2023 [152]

- automated search for multi-wavelength counterparts
- manual search for spectral types, orbital parameters...



→ GitHub/HMXBwebcat

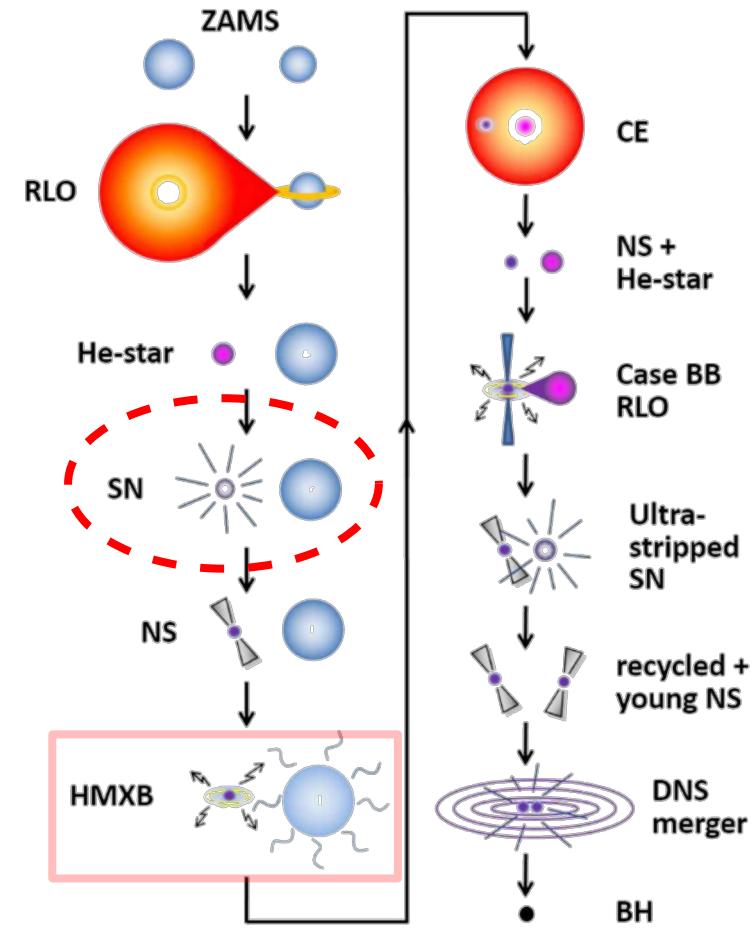


# Observing the history of binary star systems

I – A catalogue of HMXBs in the Galaxy

II – Impact of the natal kick in binaries

III – Finding the birthplace of stellar systems



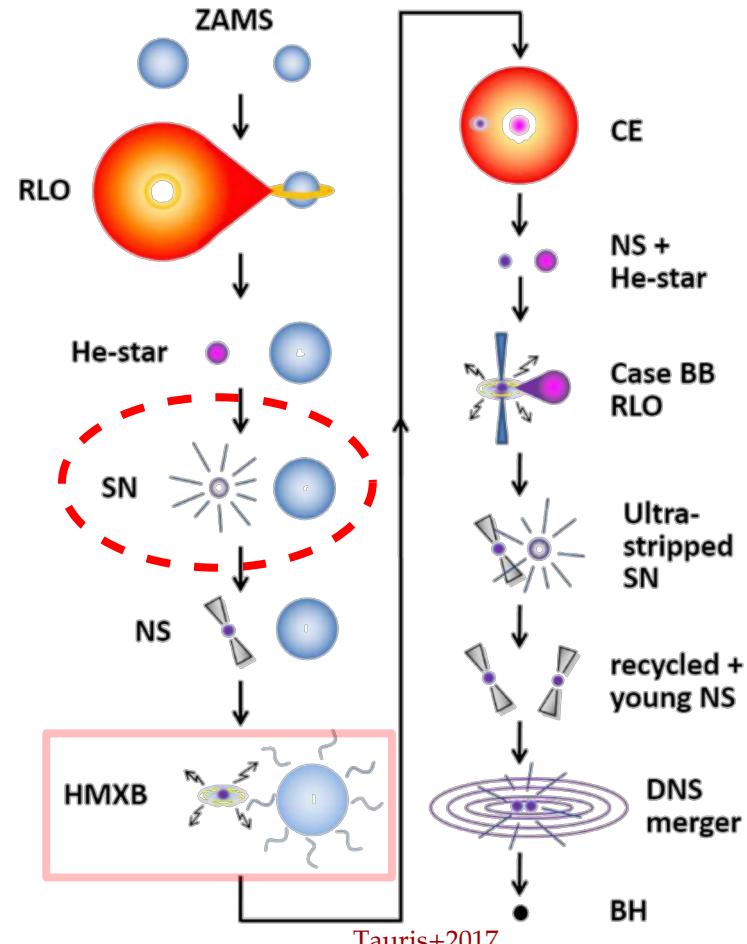
# Evolution of High-Mass X-ray Binaries

Supernova event associated with the formation  
of the compact object  
→ explosion = mass loss + asymmetry

Orbital parameters govern how binaries will evolve

Survival rate ?

Impact on orbit ?



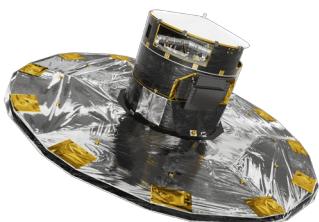
Tauris+2017

# Pre-requisites

- i) Have a catalogue of HMXBs (done !)
- ii) Compute their peculiar velocity

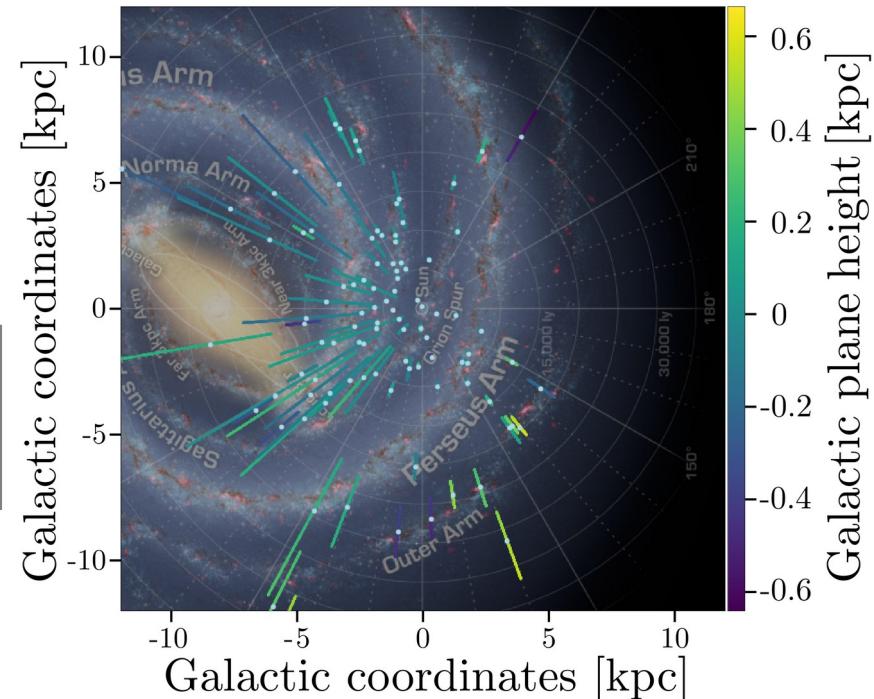
→ 6D data (position + proper motion + radial velocity)

Peculiar Velocity = Velocity – Galactic orbital motion



**Gaia:** astrometric optical survey

→ sky position + distance + proper motion



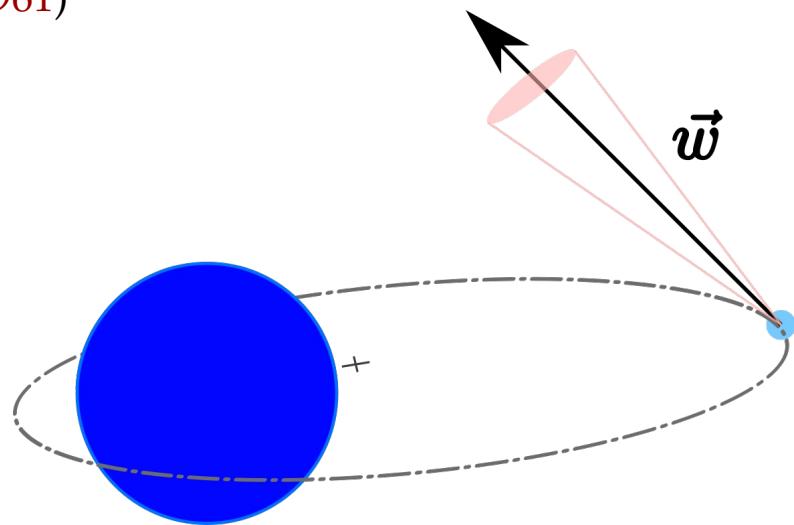
# Deriving neutron star kicks

Analytical equation linking pre-SN to post-SN orbital parameters ([Kalogera 1996](#)),  
assuming an **isotropic probability of the kick direction**.

- Blaauw kick (spherically symmetric mass loss, [Blaauw 1961](#))
- Asymmetric kick (random direction)

## Hypotheses:

- circularized systems [Dosopoulou & Kalogera 2016](#)
- fixed NS mass @  $1.4M_{\text{Sun}}$  [Kiziltan+2013](#)
- companion is unaffected by the supernova [Liu+2015](#)

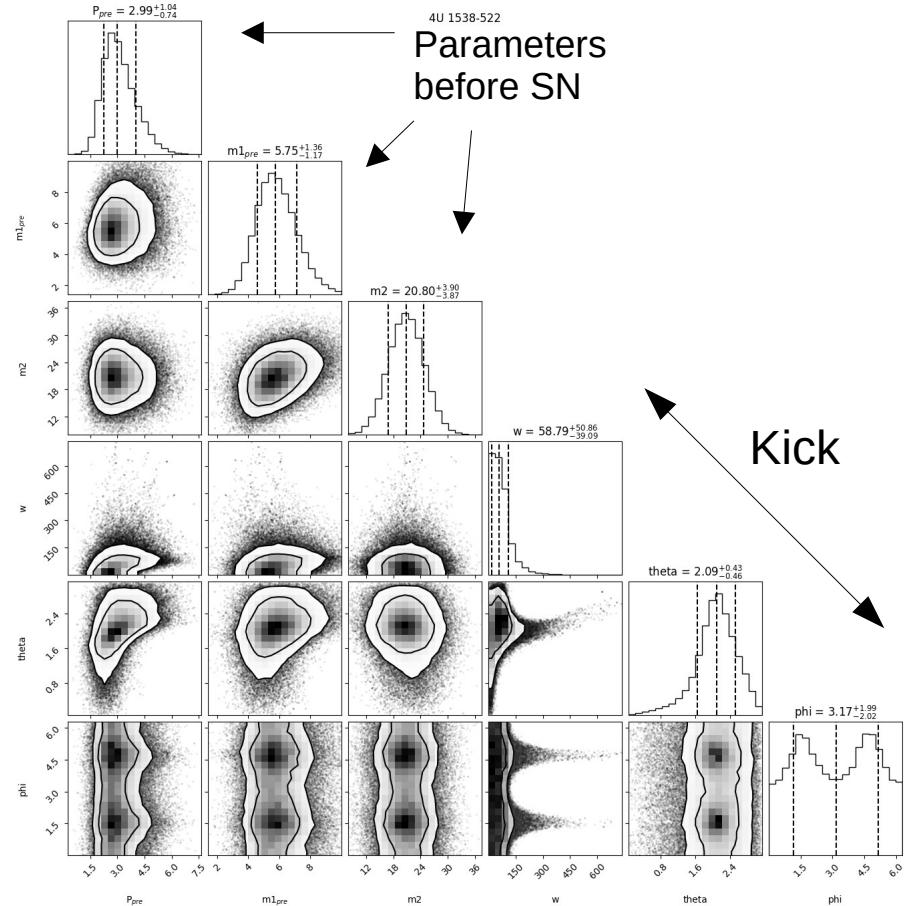


# Deriving neutron star kicks

## Bayesian approach:

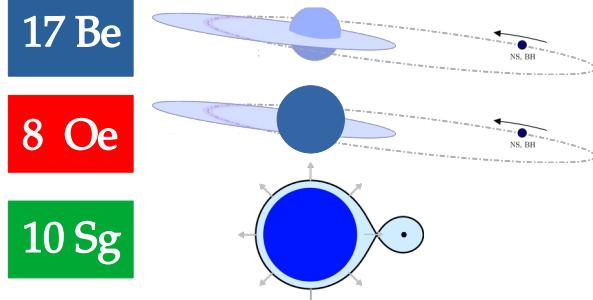
- Priors on kick magnitude, initial  $P_{\text{orb}}$  and pre-SN mass
- Likelihoods: Gaia observables, companion mass,  $P_{\text{orb}}$  & eccentricity

→ Explore the posterior distributions using Markov Chain Monte Carlo (MCMC)



# Results on kick distributions

Inferred kick magnitudes on 35 HMXB :

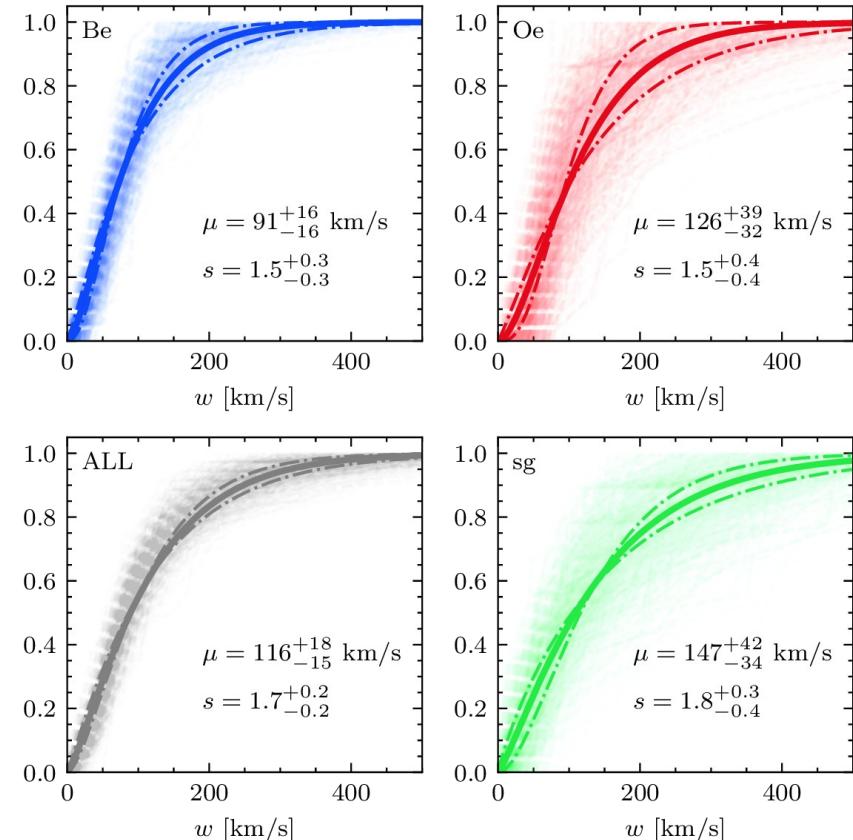


Kick magnitude + pre-SN mass + disrupted fraction

Low natal kicks: stripped SN events

→ useful for population synthesis models ?

Cumulative distributions of kicks

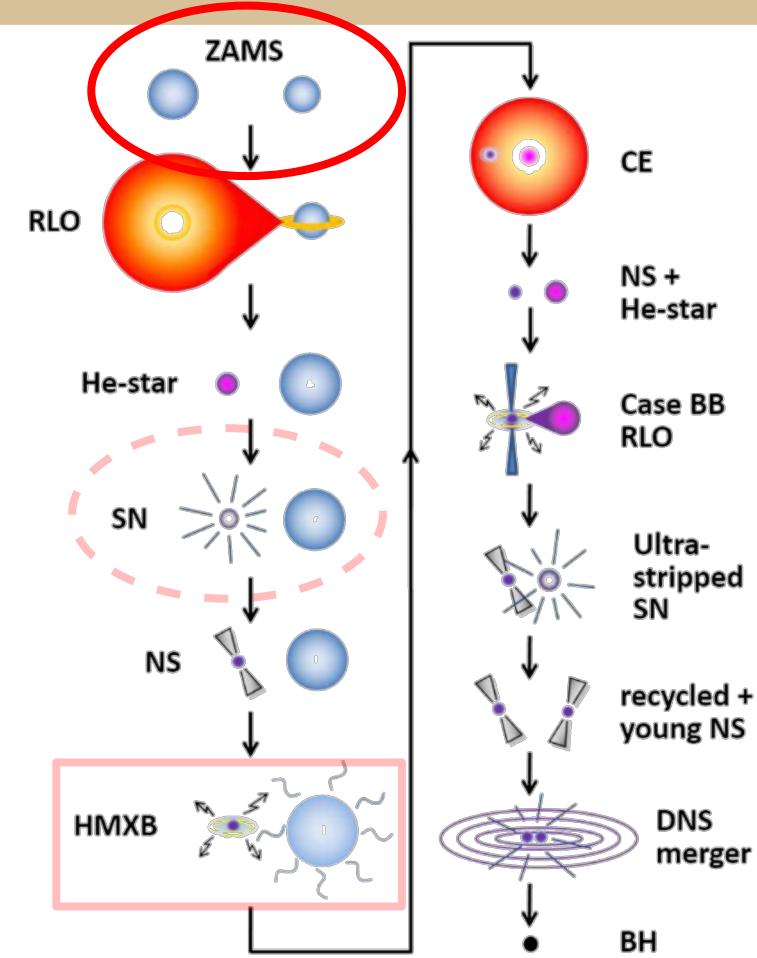


# Observing the history of binary star systems

I – A catalogue of HMXBs in the Galaxy

II – Impact of the natal kick in binaries

III – Finding the birthplace of stellar systems



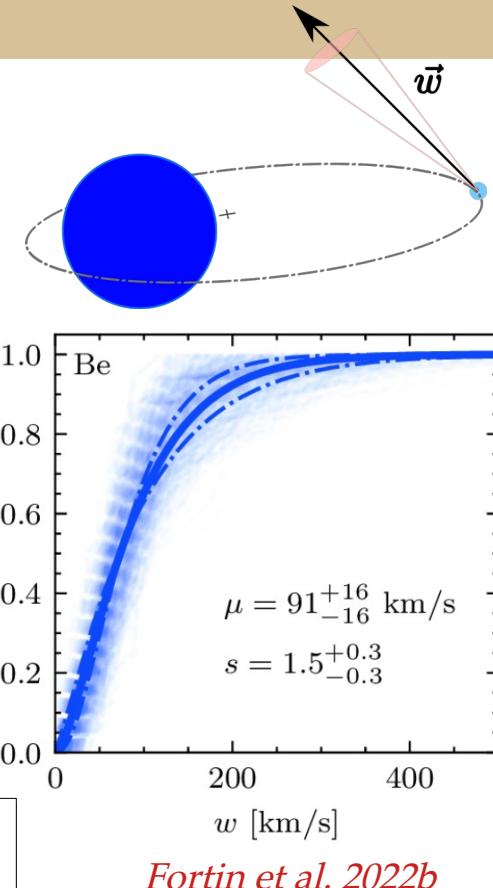
# Natal kick & migration from birth site

Supernova event = neutron star (or black hole) **natal kick**.

- impact on orbital parameters ( $P_{\text{orb}}$ , eccentricity)
- survivability (large kick → unbound system ?)
- **imprint on the peculiar velocity of the whole system**

Order of magnitude :  $V_{\text{pec}} \sim 100 \text{ km/s} \rightarrow \text{migration of } \sim 100 \text{ pc/Myr}$

Even if HMXBs are young (few dozen Myr), migration distance can be high.



# Birthplace of HMXBs and Galactic ecology

- Galactic structures susceptible of hosting massive star formation :  
young open clusters, spiral arms, isolated ?

Question

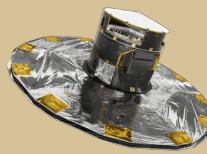
How do HMXBs fit in the Galactic ecology ?

What  
we get

Infer the age of HMXBs since the first supernova event  
→ evolution timescales, formation scenarios, history...

Correlation between spiral arms and/or OB associations in Milky Way : **Bodaghee+2012, Coleiro+2013**  
→ Need accurate kinematical data !

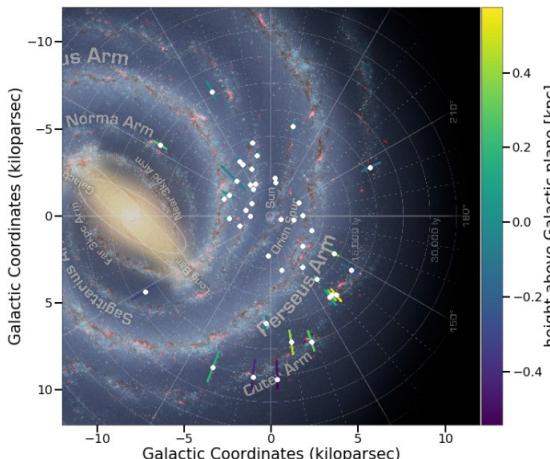
# Astrometry from Gaia EDR3



## High-Mass X-ray Binaries

Fortin+2022b

- 94 confirmed in Milky Way
- 80 observed by Gaia
- 26 with full 6-D astrometry**

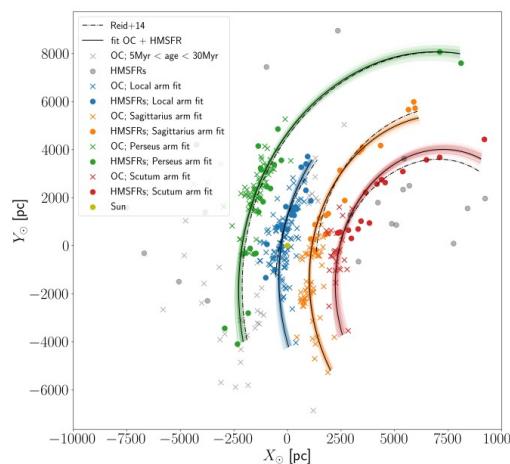


## Galactic spiral arms

Castro-Ginard+2021

- Local, Sagittarius, Perseus, Scutum
- shape + motion

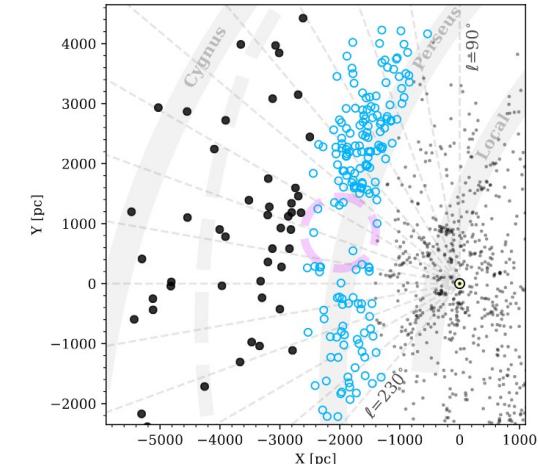
$$\ln \frac{R_G}{R_{G,\text{ref}}} = -(\theta_G - \theta_{G,\text{ref}}) \tan \psi$$



## Open stellar clusters

Cantat-Gaudin+2020

- 2017 within ~5kpc
- age from HR isochrone fitting
- 1381 with full 6-D astrometry**



# Integration of orbit around the Milky Way

- Use of python module *Galpy* to initialize & integrate the motion of HMXBs and clusters
- MWPotential2014 (**Bovy 2015**) : bulge + disk + dark matter halo
- 500 timesteps of 0.2 Myr → explore the orbits until 100 Myr ago

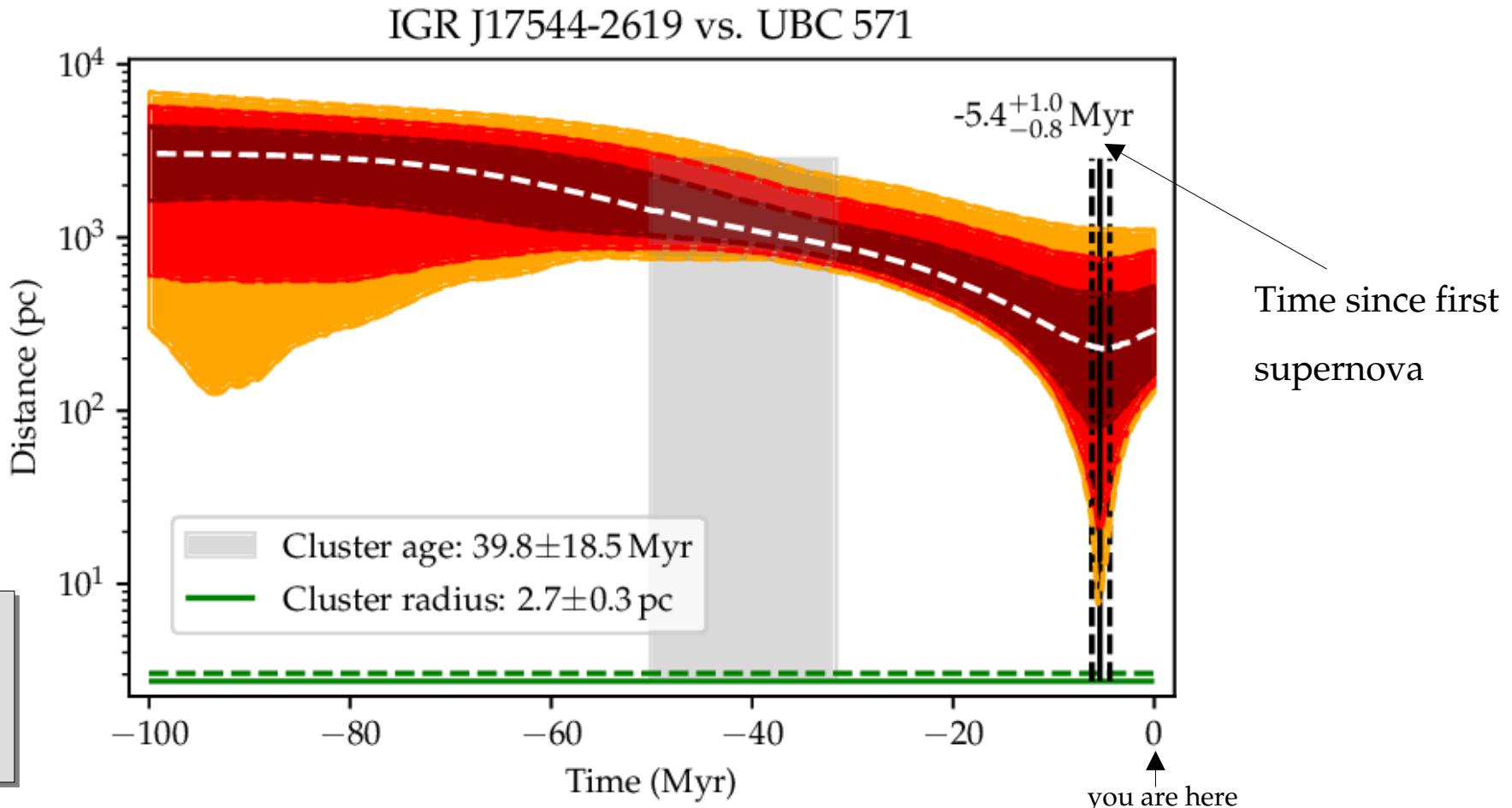


Gaia astrometry is very accurate ! ... but not perfect :(

→ 1000 orbit integrations using initial parameters drawn from distributions according to Gaia data

- We obtain, for each timestep, a distribution of possible positions & velocities
  - Compute the possible distances to clusters and spiral arms to find **encounter candidates**.
  - simple galactic potential, low sample size → not too CPU-intensive

# Encounter detection: time-distance histograms



# General results – Birthplace statistics

Open Cluster	tSN [Myr]
1A 0114+650.....	4.4
LS I+61 303.....	15
X Per.....	24
HD 259440.....	38
4U 1700-377.....	1.9
IGR J17544-2619.....	5.4
Cyg X-1.....	4.4

7

Spiral arm	tSN [Myr]
1A 0535+262.....	18
2FGL J1019.0-5856 .....	10
Cen X-3.....	1.9
1E 1145.1-6141 .....	25
4U 1538-522 .....	10
IGR J18450-0435.....	20
SS 433 .....	<60
4U 2206+543.....	25

8

Isolated ?
IGR J00370+6122
IGR J08408-4503
Vela X-1
GX 301-2
PSR B1259-63
LS 5039
MWC 656

7

Happy birthday !

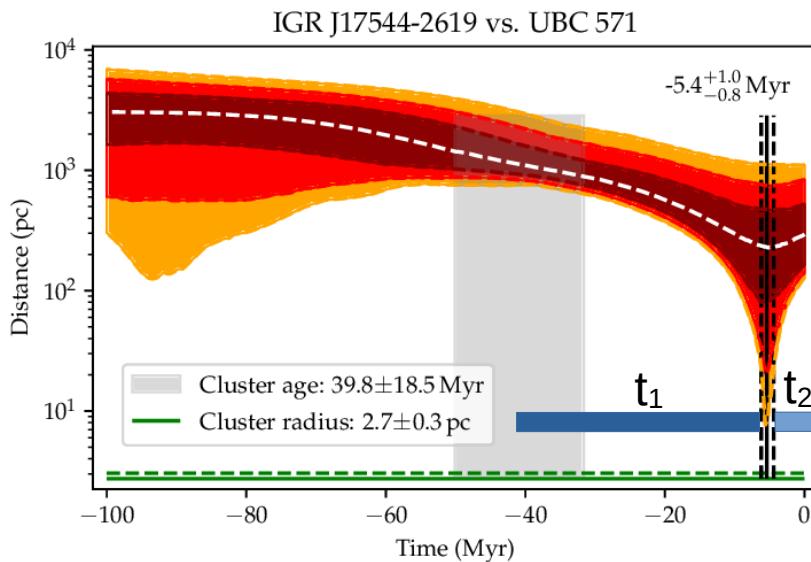
:)

- HMXBs can have encounters with both clusters and spiral arms
- degeneracy is always lifted when taking into account companion mass & evolution timescales

# Actual results : ZAMS masses, and more

Mass – Age relation for massive stars ( $10 - 60 M_{\odot}$ ) :  $\frac{M}{M_{\odot}} = \left[ 10^{-4} \left( \frac{t_{ZAMS}}{\text{Myr}} \right) \right]^{\frac{1}{1-\alpha}}$ ;  $\alpha = 3.125$  (Figueiredo+1991)

Cluster encounters give primary star lifetime ( $t_1$ ) and age since supernova ( $t_2$ ) :



$$t_1 \rightarrow M_{1,i} = 14.4 \pm 0.2 M_{\odot}$$

$$t_1 + t_2 \rightarrow M_{2,i} \leq 13.5 \pm 1.8 M_{\odot}$$

Primary ZAMS mass

Secondary ZAMS mass (upper limit)

$$M_{2,f} = 23 M_{\odot} \rightarrow M_{\text{acc}} \geq 9.5 M_{\odot}$$

Initial mass transfer (lower limit)

$$M_{1,\text{pre-SN}} \leq 4.9 M_{\odot}$$

Pre-supernova mass (upper limit)

→ Binary evolution through kinematics

# Conclusion & Prospects

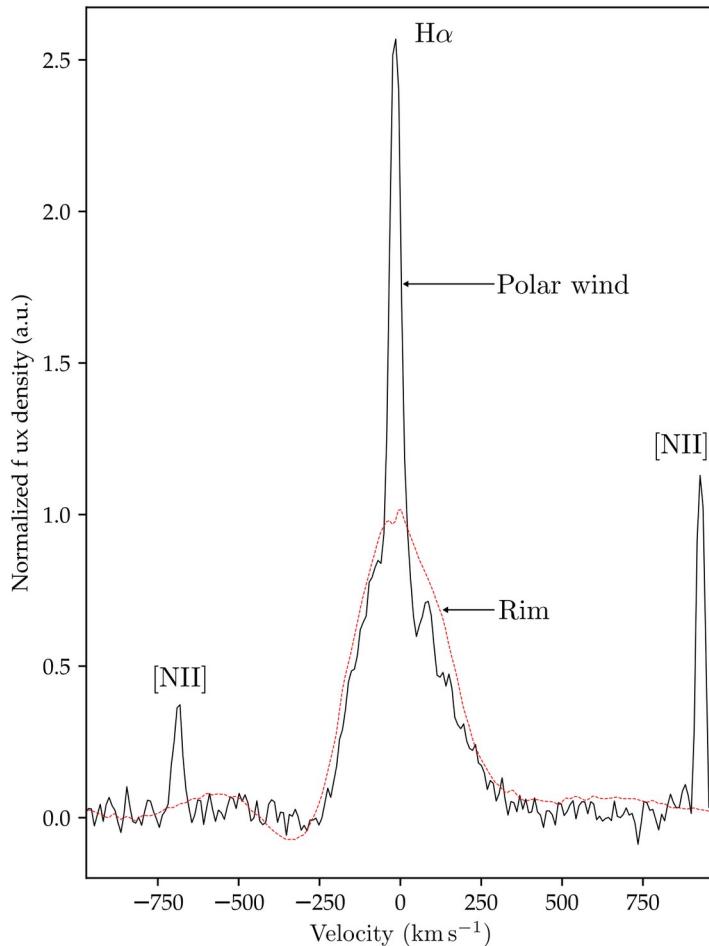
- X-ray binaries are challenging to observe
  - the latest catalogue updates the INTEGRAL – Gaia era
- We can observe their past using current optical/IR facilities
  - constraining impact of first supernova
  - date & place of birth : binary evolution history



- Next generation of observatories coming right now !  
LSST, SVOM, eRosita (?), and Athena later on
- Gravitational waves: probing the future of X-ray binaries  
LIGO/Virgo/KAGRA O4 coming on May 24<sup>th</sup> for 18 months,  
hopefully lots of neutron star merger events like 17/08/2017

Thanks for listening !

# Extra: fast polar wind ?



- depolarization across Halpha line in sgB[e] rms 82 (Seriacopi+2017)
  - produced in a large volume around the star
- no sign of narrow features in other HI (disk rim)
- if polar wind, assume  $v \sim 1000 \text{ km.s}^{-1}$ 
  - inclination angle is  $\sim 88^\circ$ , otherwise we should see double-peaked line

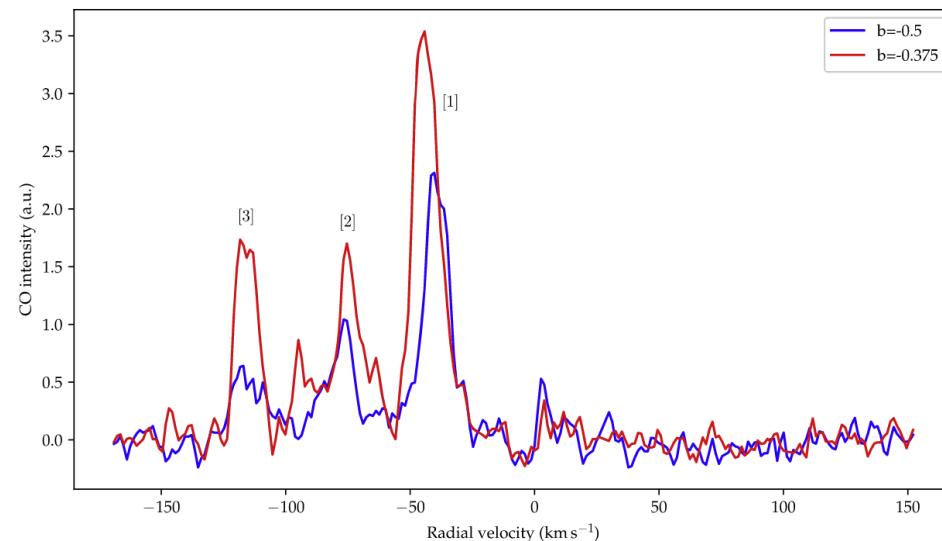
# Extra: distance to the binary

- Very absorbed → Gaia parallax poorly constrained (in all data releases)
- Bayesian inference to invert parallax from [Bailer-Jones+2020](#):  $5 \pm 3$  kpc
- Two star forming regions nearby at 2.4 and 4.9 kpc ([Russeil 2003](#))
- Recovered their position in Galactic spiral arms from [Dame+2001](#) by matching radial velocities

→ radial velocity of IGR J16318 is compatible  
with the SFR at 4.9 kpc.

→ incorporate this in Bayesian scheme & Gaia data:

$$D = 4.9 (+1.9 -1.5) \text{ kpc.}$$

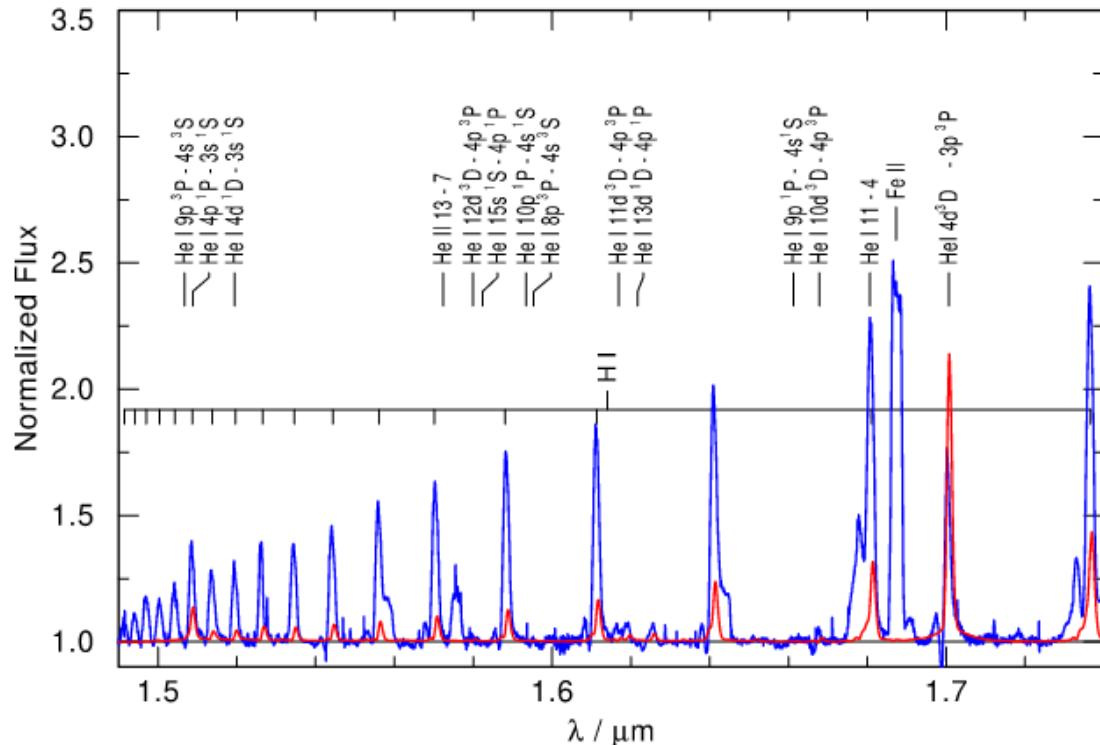


# Extra: stellar atmosphere & wind modeling

- HI lines barely reproduced
- good agreement with HeI lines
- same wind velocity ( $\sim 400 \text{ km.s}^{-1}$ )

→ confirms HI mainly comes from rim  
→ highly He-enhanced star ?

PoWR code output compared to observed spectrum:



# Disrupted systems, isolated NS velocities

Tauris & Takens 1998 : equations for velocity of a NS kicked-out of the binary after the SN event

Observed velocity distribution of isolated radio pulsars :

Hobbs+2005 → 265 km/s

Igoshev 2020 → 230 km/s (or 146 + 317 km/s)

We keep track of disrupted systems (5 to 50% of simulation outcomes depending on the binary)

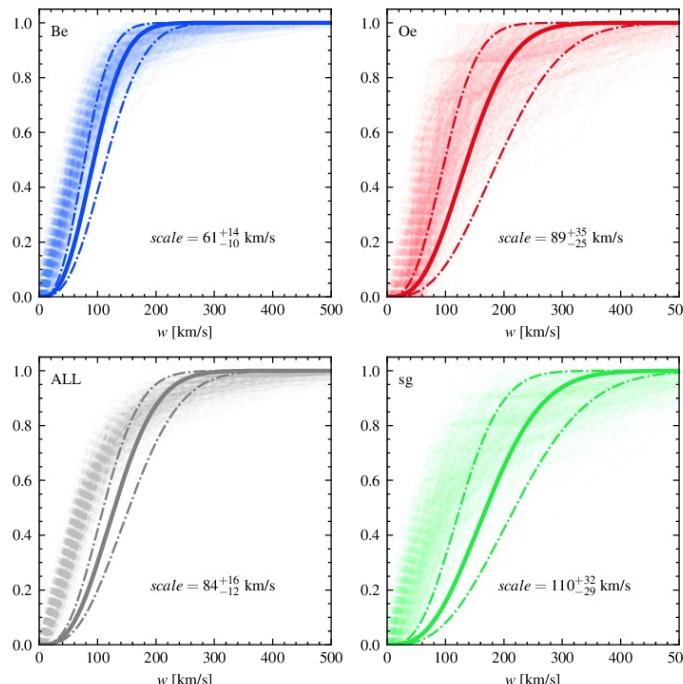
→ NS velocity from disrupted systems in our sample : 110 km/s

→ In case of disruption, < 3% result in fast pulsars (> 500 km/s, large initial period > 1000 d required)

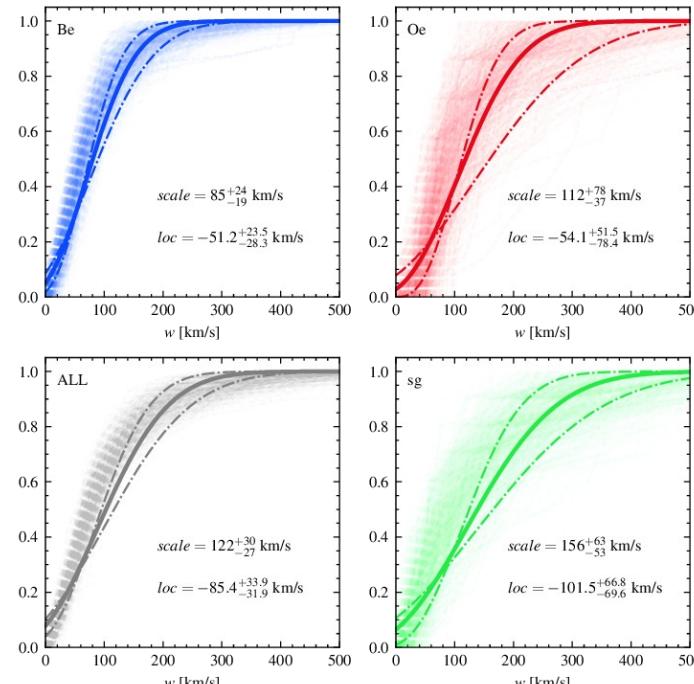
→ Binary evolution unlikely to be a formation channel for fast isolated NS.

# Extra: Maxwellian vs. Gamma

Maxwellian is historically used to model kicks in isolated pulsars (Hobbs+2005, Ng & Romani 2007, Noutsos+2013)



Classical Maxwellian



Shifted Maxwellian

Unbound systems ?

→ observed vs. pop synth.

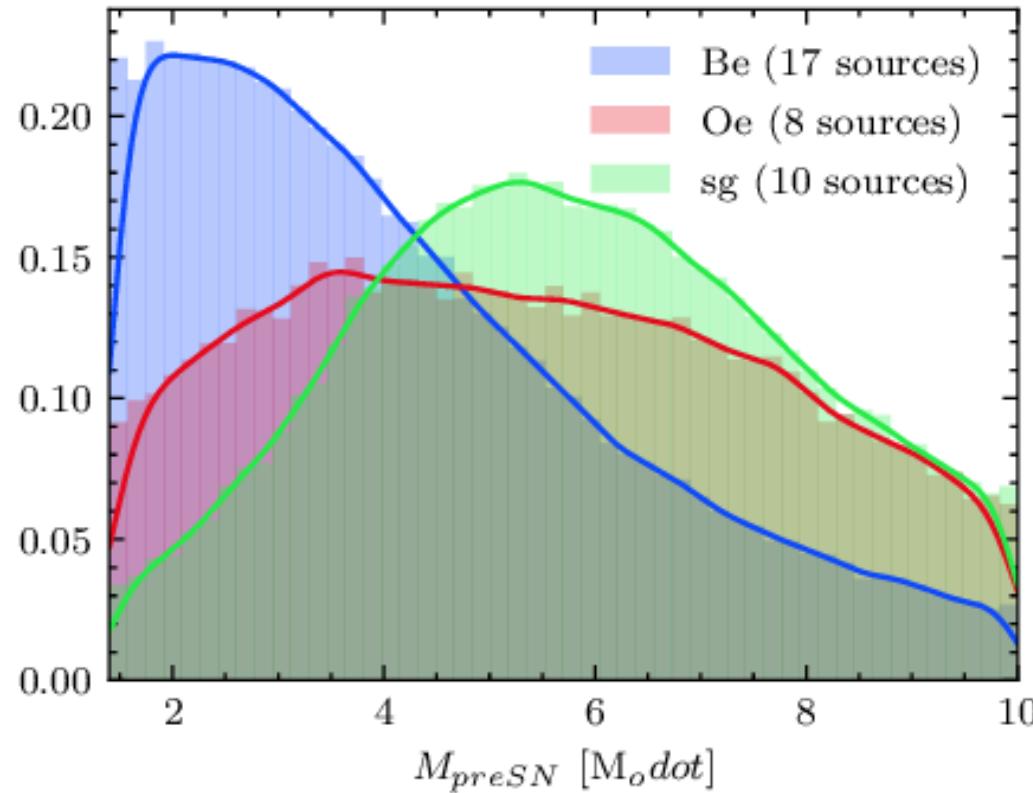
Stripped progenitors ?

→ lower pre-SN mass

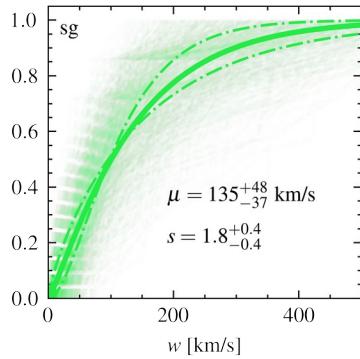
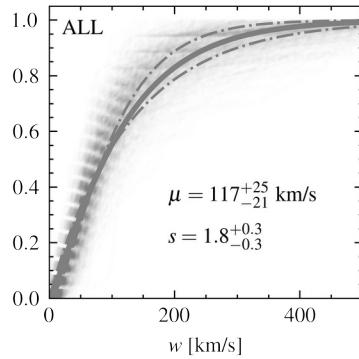
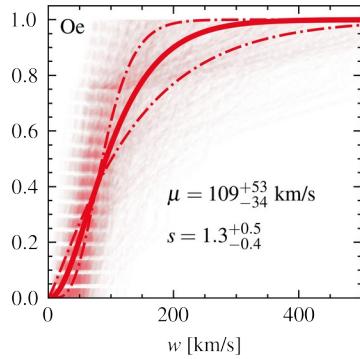
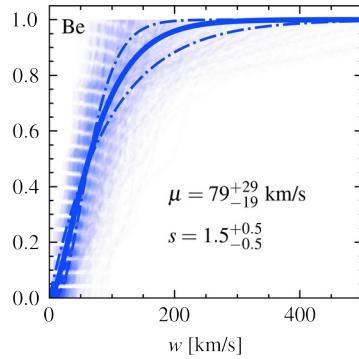
Kick isotropy ?

→ NS spin axis

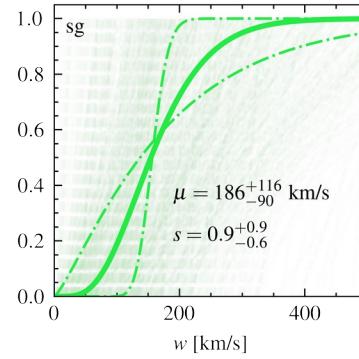
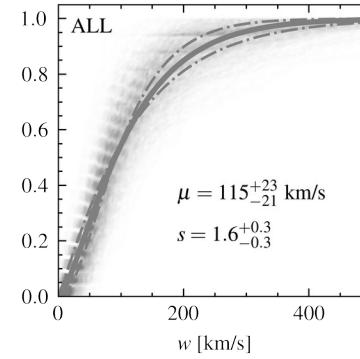
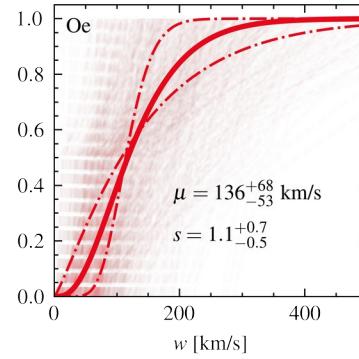
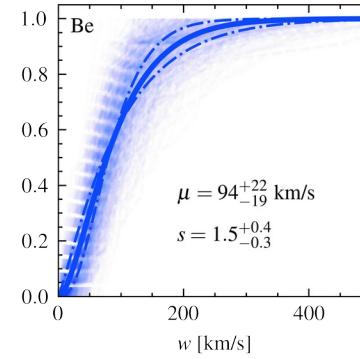
# Extra: $M_{\text{pre-SN}}$ distribution



# Extra: impact of missing radial velocity



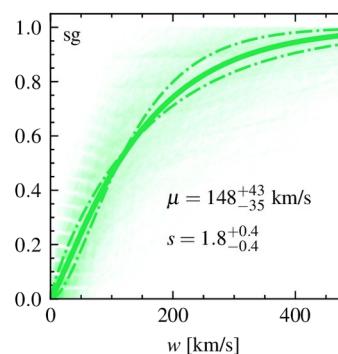
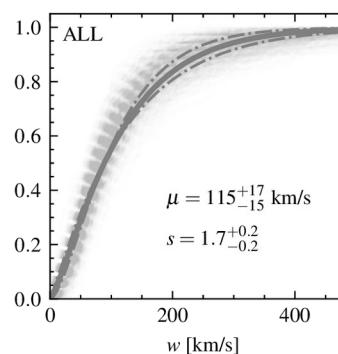
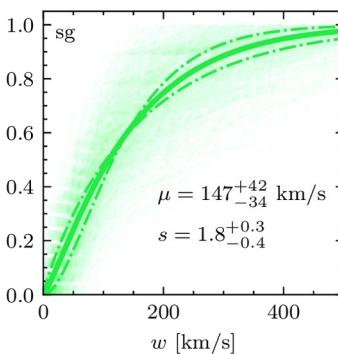
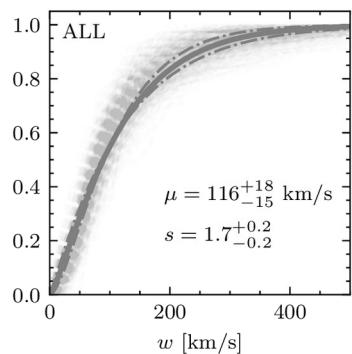
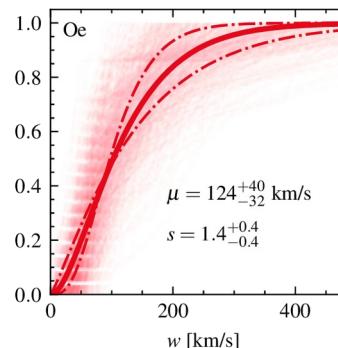
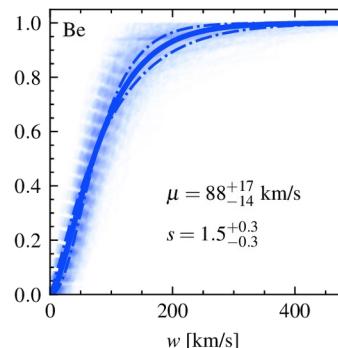
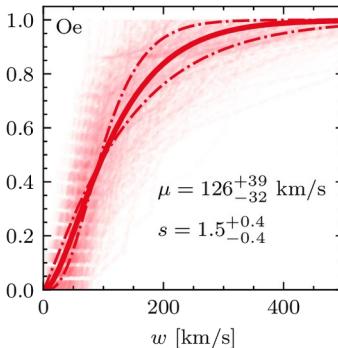
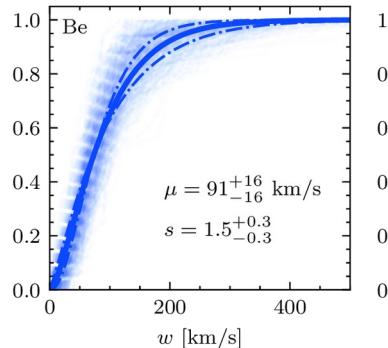
With RV only



Without RV only

# Extra: impact of neutron star mass

→ Assumed constant NS mass of 1.4 Msun, what about more massive NSs ?



$M_{\text{NS}} = 1.4 M_{\odot}$

$M_{\text{NS}} = 1.8 M_{\odot}$

No notable difference  
on the fitted  
parameters

→ NS mass variation  
are much smaller  
than  $M_{\text{pre-SN}}$   
uncertainty

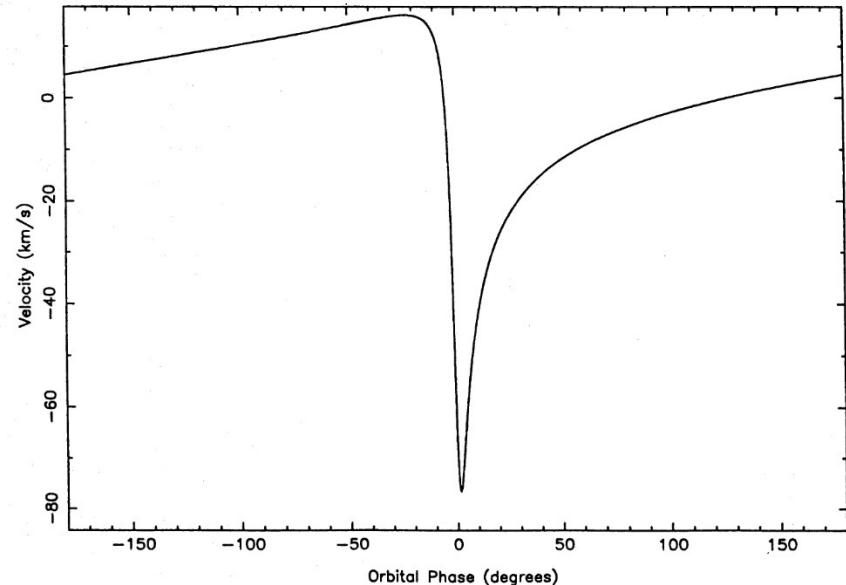
# Extra: building the list of HMXBs

## Example: PSR B1259-63

Radial velocity followup of the Oe companion star  
→ Curve is presented but no value of the systemic velocity is given in the paper !

→ WebPlotDigitizer: we retrieved the data from the plot and fitted the systemic velocity

→ Do that for 130 HMXBs in the Galaxy.



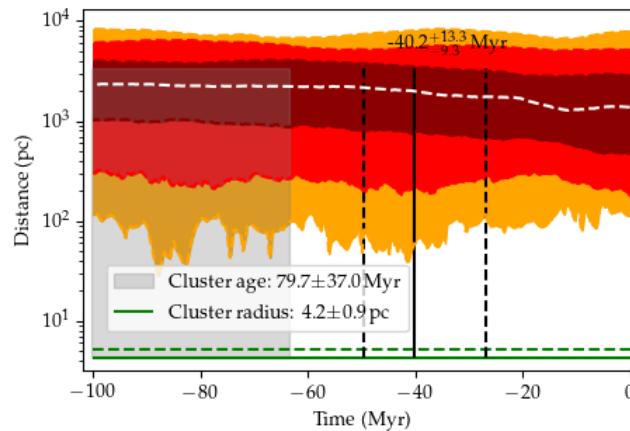
Radial velocity of PSR B1259-63 (Johnston+1994)

# Encounter detection : validity of the method

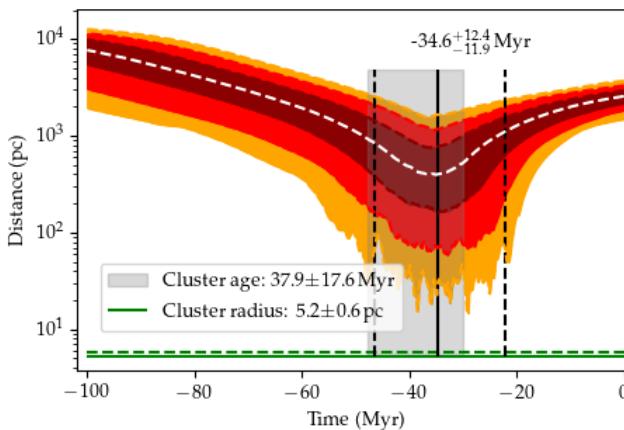
→ Simulations over randomly generated HMXBs and clusters to test the ability to find a birthplace

- chose a random birth date in [1 : 100] Myr
- initialize a birth cluster at a random position + velocity
- initialize HMXB born somewhere near the cluster
- apply random natal kick to HMXB
- integrate both orbits up until today
- generate dummy Gaia astrometry for HMXB & cluster of random quality (according to real data)
- look for an encounter

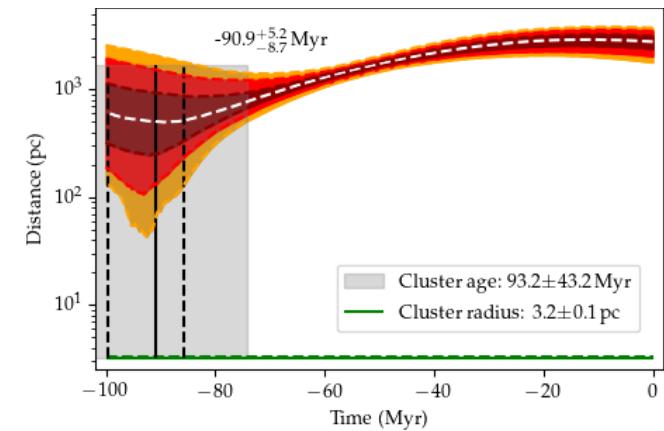
# Encounter detection : validity of the method



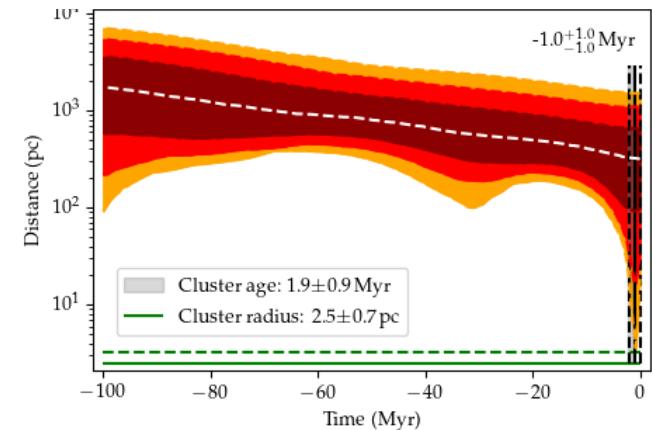
← Bad astrometry : 10% failed cases



Good astrometry →  
retrieve old encounters



produce both sharp →  
← and wide distributions



# Galactic distribution of Gaia clusters & HMXBs

- Gaia parallax → distances  $\lesssim 5\text{kpc}$
- drastic decrease in known clusters with distance

